Proceedings of Korean Nuclear Society Autumn Meeting
Taejon, Korea, October 2000

Development of Long Term Cooling Analysis Model for ULOHS Accident in KALIMER

Won Pyo Chang, Kwan Seong Jeong, Young Min Kwon, Yong Bum Lee, Dohee Hahn

Korea Atomic Energy Research Institute
P.O.Box 105, Yusung, Taejon, Korea, 305-600

Abstract

The KALIMER design adopts PSDRS(**P**assive **S**afety **D**ecay **H**eat **R**emoval **S**ystem), which use a passive way to remove the decay heat, as an ultimate heat sink for the loss of heat sink accident. The system removes the heat generated in the reactor core by cooling the containment vessel wall through natural circulation. The top-tier requirement of the KALIMER conceptual design excludes an operator action for 72 hours when an accident occurs. So, it is necessary to estimate the time and coolant temperature when the ultimate balance between the core heat generation and heat removal is made, for assessment of the design safety. However, since SSC-K takes long calculation time as well as generates enormous output hard to handle for the ULOHS analysis, it is not adequate to apply SSC-K code to the accident. The present study is to develop a model capable of analyzing the long term cooling to overcome the difficulty, by extrapolating the calculation results from the system analysis code SSC-K. The model simplifies the KALIMER system based on reasonable assumptions for such long time simulation. Analysis of the long term cooling capability of KALIMER is also performed using the developed model in the present study.

1. Introduction

In the KALIMER design [1], the loss of heat sink accident is presumed to occur if IHTS (**I**ntermediate **H**eat **T**ransportation **S**ystem) is isolated to prevent the potential for the propagation of sodium-water chemical reaction in a sodium-to-water heat exchanger (Steam Generator), if an IHTS pipe is ruptured, or if the rupture disk bursts. [2] The accident is assumed to begin with a sudden loss of the normal heat sink by sudden stoppage of the IHTS flow. Natural circulation in IHTS is ignored so that this event is similar to complete loss of coolant in IHTS, as would be true for the pipe rupture or the rupture disk burst. All heat generated in the core is, thus, retained in the primary vessel. PSDRS is designed to avoid such unlimited heat up of the primary system, which could lead to significant core damage and offsite release of radioactive material.

According to the safety criteria developed for the KALIMER design [3], the system should return to the safe state without an operator action for 72 hrs after accidents. Obviously, a concern comes up with whether the PSDRS is capable of removing the heat generated in the primary system alone. Thus, the safety analysis [4] was carried out using SSC-K, to find what the sodium temperature and safety margin in the primary system would be, and whether the heat removal capability of the PSDRS would be enough under the accident. The analysis was based on an assumption of the unprotected accident, which preclude the reactor trip actuated by the high core outlet sodium temperature. The primary pumps (four pumps) were also unprotected because they are not designed to trip before the core protection system actuates. The primary pumps are designed to operate at the rated conditions until tripped by the pump protection system, a safety grade system to open the pump breakers if the primary cold leg temperature exceeds the setpoint. The main objective in the analysis was to confirm inherent safety characteristic of the KALIMER for the Plutonium fueled core. The analysis result showed that the automatic control system and operator actions are of importance because the primary pumps contribute a major heat source to PSDRS for the long term cooling. The analysis, however, was limited to 40,000 sec, because the simulation time was too long and the outputs were enormous. Therefore, a question how to estimate the time and coolant temperature will be when the ultimate balance between the core heat generation and heat removal is made, is still remained. As a solution for the problem, the present model has been developed. The model simplifies the system based on reasonable assumptions for such long time simulation and uses the necessary parameters from SSC-K results at a reasonable time as an initial condition, in order to extend the parameters up to 72 hours after the accident.

2. Modeling

2.1 Energy Balance Equations

The primary system of KALIMER is primarily modeled with a single control volume with two kinds of structure materials. The following assumptions are possible based on this simplification :

(1) The temperatures of the hot and cold pools are same.
(2) The sodium levels in the hot and cold pools are same and move simultaneously depending on the energy balance, so that the whole primary coolant system can be represented with a single lumped system.
(3) Each of the two structure materials can also be lumped together, which means that each one is represented with a constant heat capacity and a single temperature.

It is recognized that the cold pool temperature nearly approaches to the hot pool temperature soon after the accident occurrence and both temperatures behave similarly thereafter from the analysis[4]. A mid-value between the hot and cold levels is taken as the lumped sodium level. The relative error of the level difference between two pools after sodium overflow from the hot to cold pool is estimated less than 2.0 % to the cold pool level. It, nevertheless, does not seem to give a significant effect on the PSDRS heat removal even when the pumps are operating, because the sodium temperature is usually more sensitive to the PSDRS heat removal. Therefore, the assumptions used are considered reasonable.

Figure 1 illustrates the modeling developed in the study. All coolant volumes inside the primary vessel are represented with a single volume where two heat conduction structures are submerged. The heat generated in the volume is removed by both PSDRS and transferred to the structures. Thus, the energy balance equation is given by

$$m_{Na} C_{Na} \frac{dT}{dq} = Q_c - Q_{Stru} - Q_{psdrs} \tag{1}$$

where,

m_{Na} : Total mass of sodium in the primary vessel (kg)

C_{Na} : Specific heat of sodium (J/kg-K)

T : Sodium Temperature (K)
θ : Time (s)
Q_c : Heat generation rate in the core (W)

Q_{stru} : Heat transfer to the structure materials (W)
Q_{psdrs} : PSDRS heat removal rate (W)

In the sodium mass estimation, the pre-calculated volumes inside the primary vessel given in Fig. 2, are multiplied by density of sodium corresponding to each volume temperature. Then, the average cross sectional area of the volume is obtained by dividing the total sodium volume by the average sodium height at the time when the present simulation begins. According to the previous result [3], the core heat generation drops to the decay heat level within 1,000 s. The core decay powers vs. time used in this simulation are presented in Table 1. The actual heat generation in the reactor is the value that the pump heat (0.8 MW per a pump) is added to a given decay power. The model also takes into account the heat capacities of the structure materials, that are the baffle plate, the thermal linear, the IVTM (In-Vessel Transfer Machine) and the UIS (Upper Internal Structure). The balance equations for them are given by

$$m_1 C_1 \frac{dT_{m1}}{dq} = U_1 A_1 (T_{Na} - T_{m1}) \tag{2}$$

$$m_2 C_2 \frac{dT_{m2}}{dq} = U_2 A_2 (T_{Na} - T_{m2}) \tag{3}$$

where,

m_1 : Total mass of the baffle and the thermal linear (kg)
m_2 : Total mass of the IVTM and UIS submerged in the hot pool (kg)
T_{m1}, T_{m2} : Each structure temperature (K)
U_i : Overall heat transfer coefficient (W/m^2-K)
A_i : Heat transfer area of structures (m^2)

and the amount of energy transferred to the structures is estimated with :

$$Q_{stru} = U_1 A_1 (T_{Na} - T_{m1}) + U_2 A_2 (T_{Na} - T_{m2}) \tag{4}$$

For the calculation of the heat removal by PSDRS, the model previously developed [5] is applied.

Qc is first determined from Table 1 with table look-up and Qstru is then estimated from Eq. (4) with given sodium and structure temperatures. Finally, Qpsdrs is obtained from the PSDRS model. The temperature gradient now can be calculated using values of Qc, Qstru, and Qpsdrs from Eq. (1). One can get the new sodium temperature easily by integrating Eq. (1) explicitly (Eulerian Method), i.e.

$$y^{(n+1)} = y^{(n)} + y'(n) \cdot \Delta t \tag{5}$$

The structure temperatures are also obtained by integrating both Eq. (2) and (3) explicitly.

2.2 Sensitivity Study

First of all, the primary concern with the developed model is considered to be stability of the solutions for Eq. (1), (2), and (3) because explicit integration method (Eulerian Method) is used. The initial values for this model are taken from the results of ULOHS analysis at 9984 s after the accident. [4] The reason for taking the time as an initiating time for this simulation is that sodium in the hot pool sodium overflows into the cold leg so that the sodium levels in the pools are almost same and increase similarly from this time. The simulation in [4] was made for 40,000 s with SSC-K due to long CPU time. The main variables for the initial condition of this model are sodium temperature and level, and time. The time is important because it determines the decay heat level.

Stability of the solution is examined for time step, 0.1, 0.5, and 1.0 s. The time-steps smaller than 0.1 s are precluded because they have no meaning in the simple model due to long CPU time. Fig. 2, 3, and 4 present the comparison results for sodium temperature, level, and PSDRS heat removal, respectively, with different time-steps. As seen from the figures, the calculated parameters do not show any abnormal behavior, which indicates that the solutions are quite stable for these time-steps. Table 2 shows a statistics for CPU time with different time-steps. It saves large computational time to take the time-step, 0.5 s and thus makes possible analyze a long-term cooling transient after ULOHS.

The next investigation find whether there is any error build-up due to the numerical method itself. A modified method that uses the average value between the previous and new time-step gradients, instead of only the previous gradient that is used in the original Eulerian method is applied, i.e.

$$y^{(n+1)} = y^{(n)} + 0.5\{ y'(n) + \tilde{y}'(n+1)\}\Delta t \tag{6}$$

This method is known to be more accurate compared with the original Eulerian method. Fig. 5, 6 compare these two methods for time-steps, 0.1 and 0.5 s, respectively. From the results, it is found that there is no propagation of an extraordinary error because the results for both methods agree well. It is noted that large time-step (> 2.0 ~ 3.0 s) results in unrealistic solution behaviors. The calculation results from the present model are compared with those from SSC-K and are shown in Fig. 7, 8, and 9. The present model generally overestimates the sodium temperature and level which lead to higher PSDRS heat removal. The temperature is overestimated by less than 0.7 % in conservative direction. Major discrepancy is likely to come from the fact that there is additional heat transfer to other structures than those modeled in the present model in the SSC-K calculation. Since heat transfer to other structures like reactor head through the cover gas region is not included in the model, the sodium temperature can be over-predicted. When the discrepancy is linearly extrapolated up to 72 hours, the maximum overestimation might be less than ~ 4 %. Therefore, it does not seem to produce any significant uncertainty to determine the system safety, because its temperature has already reached sodium boiling point (1158 ^{o}K @ 1 atm) for the case of pump on and enough margin against sodium boiling still can be maintained, particularly, for the case of pump off.

2.3 Analysis for the long-term cooling

The developed model is applied to analysis for the long term cooling under the ULOHS accident. Two cases are examined, those are, with and without pump operation. The initial values are taken from the SSC-K results at 9984.0 s, because the hot pool sodium overflows into the cold pool and sodium levels in both the hot and cold pools approach each other, so that the assumption of a single volume for sodium in the both pools is considered acceptable. A fairly large time-step 0.5 s is used compared with that used in SSC-K calculation (~ 0.125 s). Fig. 10 shows the sodium temperature behavior for 72 hours with and without pump operation. The primary system heats up until the PSDRS heat removal balances the core heat generation roughly 70 hours after the accident (Fig. 11) and, thereafter, the temperature saturates around 1274 (K) for the pump on case. On the other hand, the PSDRS heat removal balances in the early transient in the case of pump trip assumed at 10,000 s, as shown in Fig. 12. The temperature tends to descend after passing the peak value (Fig. 10). Therefore, the system seems to be stabilized and PSDRS is capable of removing the decay heat with sufficient margin.

3. Conclusion

A simplified model for analysis of long term cooling under ULOHS has been developed. The model is based on the assumption that sodium in the primary system can be lumped together. The primary system could be lumped with a single volume and energy balance is made for the core heat generation, heat transfer to the structure materials, and PSDRS heat removal. As results, the predicted sodium temperature by this model agrees with that calculated by SSC-K for 40,000 s within an acceptable level and time consumption for the calculation has been reduced by more than 50 times.

Thanks to this model, simulation for 72 hours after the accident has become possible. When the primary pumps are on, the sodium temperature saturates near the end of the transient and the temperature has exceeded sodium boiling point. On the other hand, the temperature has tended to decrease after passing the peak point and lain fairly well below boiling point at 72 hours after the accident. The difference between these two cases is pump heat generated during the operation. The heat generated by the four primary pumps is as much as 2.8 MW and it is larger than the decay heat in the later period. It affects significantly on the safety of the KALIMER long term cooling.

Therefore, the main concern is how to justify the pump off in the analysis of the ULOHS accident for the safety and how much degradation of PSDRS may be reasonable in the KALIMER design to complete the accident analysis. Those problems will be discussed separately in another subject.

References

[1] Chang Kyu Park et al., ‘KALIMER Design Concept Report’, KAERI/TR-888/97

[2] ‘Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor,’ NUREG-1368

[3] Dohee Hahn, et al., ‘Preliminary Safety Design Analysis for Key Design Features of KALIMER,’ KAERI/TR-1616/2000

[4] W.P. Chang, et al., ‘Assessment of KALIMER for Long Term Cooling Capability’, KNS Spring Meeting, May 2000

[5] W.P. Chang, et al., ‘Development of the PSDRS Model for the KALIMER System Analysis Code SSC-K’, KAERI/TR-1143/98

[6] Y. M. Kwon, et al., ‘SSC-K Code User’s Manual (Rev. 0),’ KAERI/TR-1619/2000

시 간 (초)	Decay Power (% Nominal)	시 간 (초)	Decay Power (% Nominal)
0.	6.03	3.6e3	1.39
2.	5.40	1.8e4	0.89
5.	5.01	3.6e4	0.76
10.	4.66	7.2e4	0.63
20.	4.26	1.08e5	0.56
60.	3.57	1.44e5	0.51
120.	3.14	1.80e5	0.47
180.	2.91	2.16e5	0.44
300.	2.64	2.52e5	0.42
600.	2.30	2.88e5	0.39
1.8e3	1.73		

Table 1 Decay Heat Power

Time-step (s)	CPU Time (s)	Simulation Time (s)	Temp. (^{o}K)
0.05	3138	40,000	1091.6
0.1	1468	40,000	1097.8
0.5	270	40,000	1098.8
1.0	138	40,000	1099.0
0.5	1861	260,000 (72 hr)	1274.2 (w/ pump)
0.5	2987	260,000 (72 hr)	863.1 (w/o pump)

Table 2 Comparison of CPU time using the present model

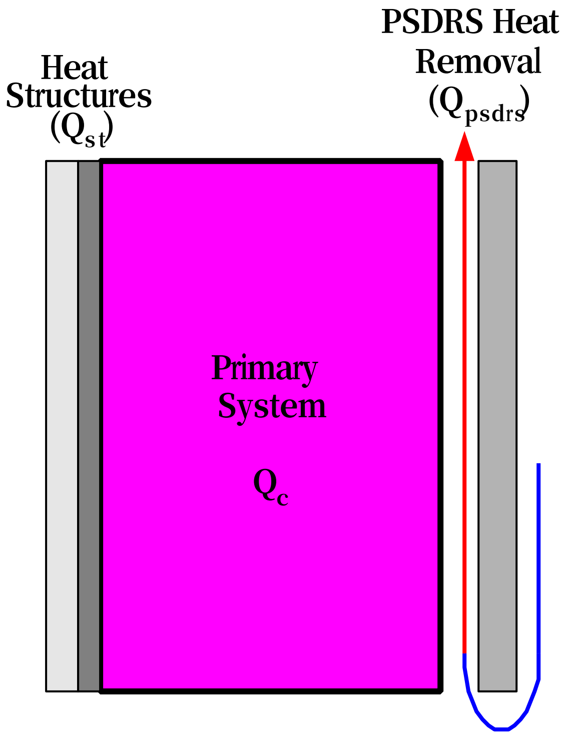

Fig. 1 Long-term cooling model

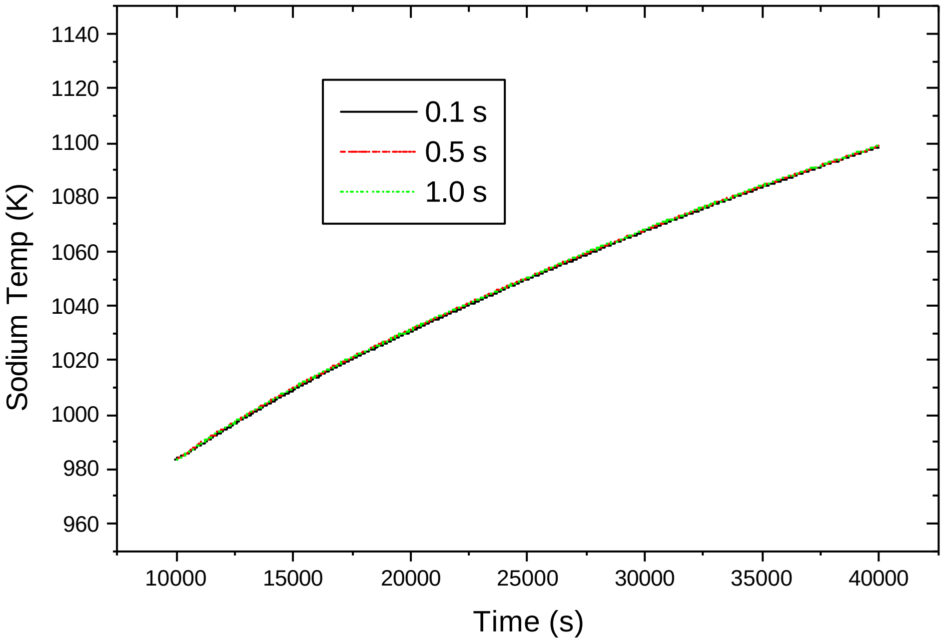

Fig. 2 Comparison of Pool Sodium Temperature with time-steps

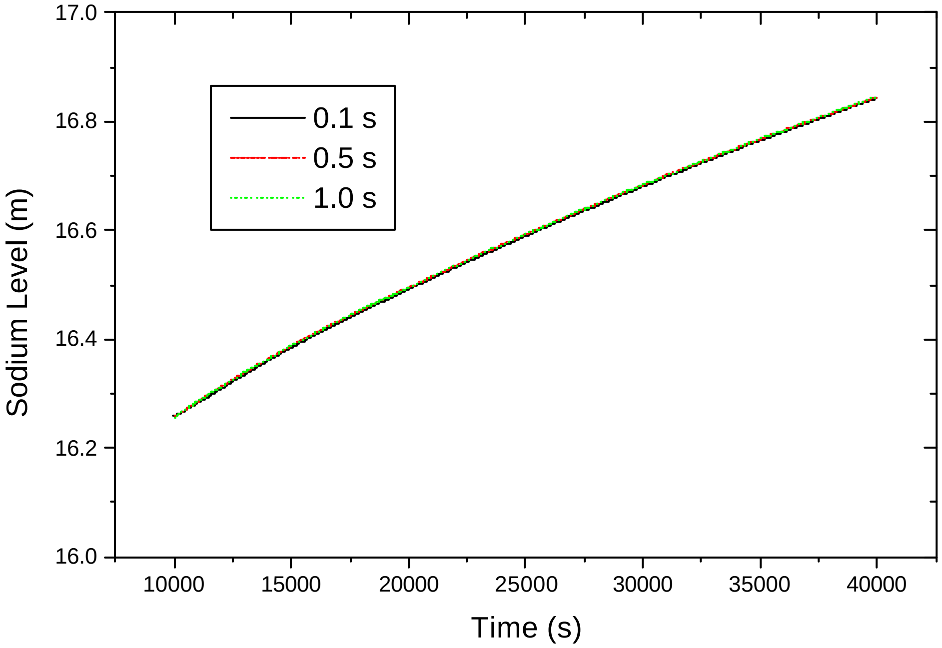

Fig. 3 Comparison of Pool Sodium Level with time-steps

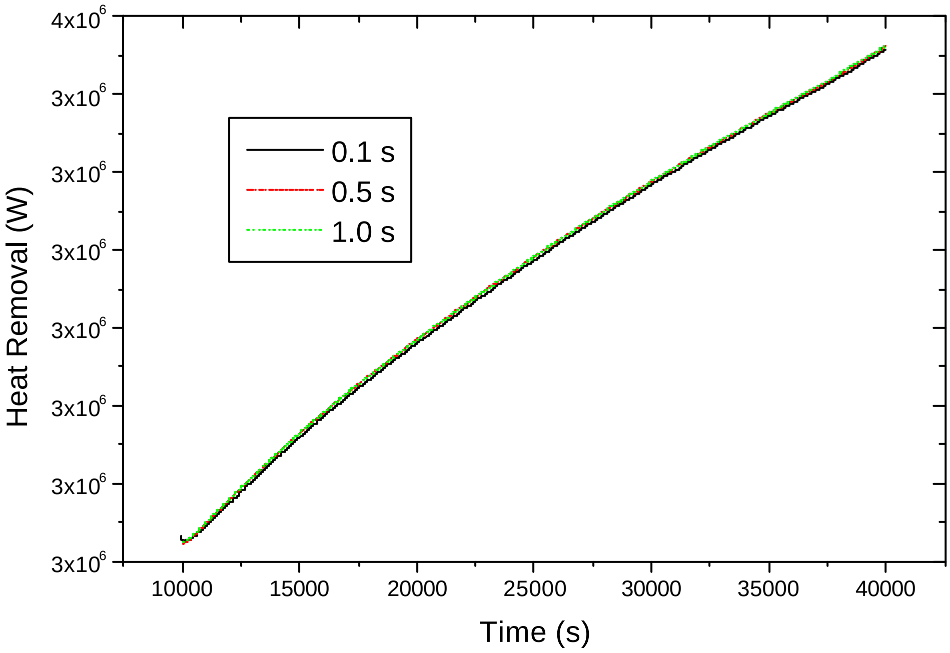

Fig. 4 Comparison of PSDRS Heat Removal with time-steps

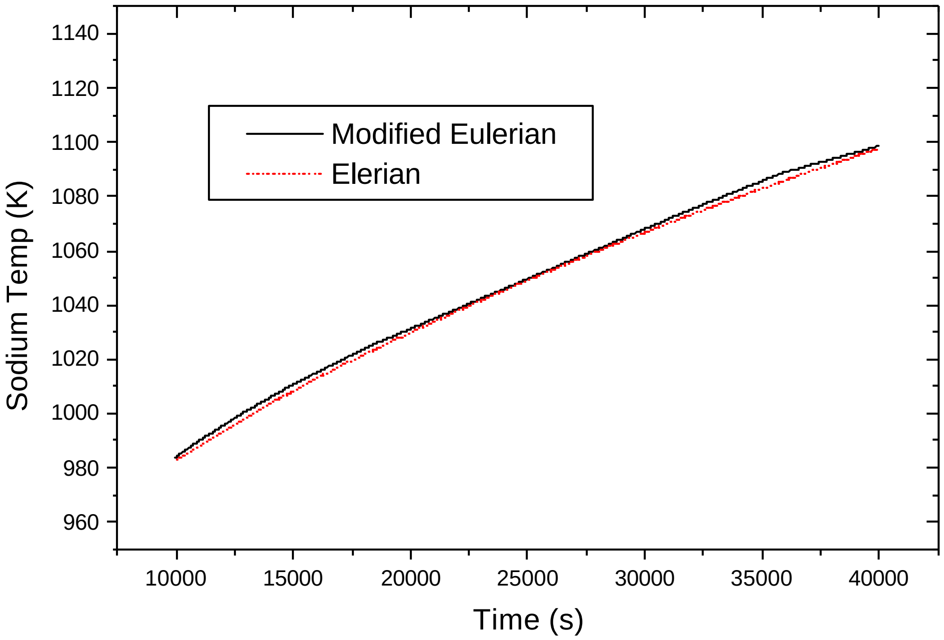

Fig. 5 Comparison of Numerical Methods for dt = 0.1

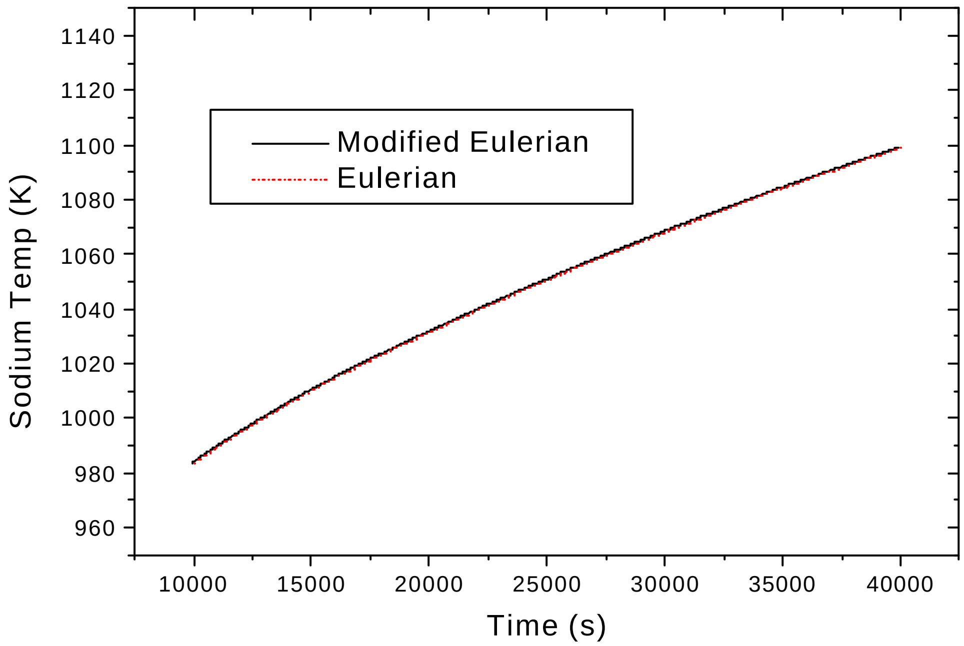

Fig. 6 Comparison of Numerical Methods for dt = 0.5

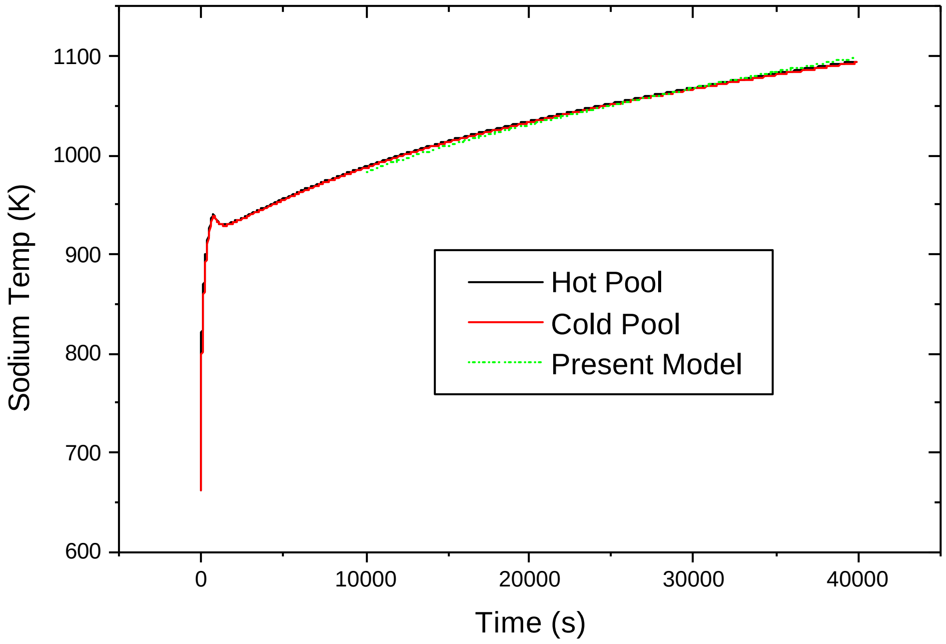

Fig. 7 Comparison of Present Model and SSC-K Calculations for Sodium Temp.

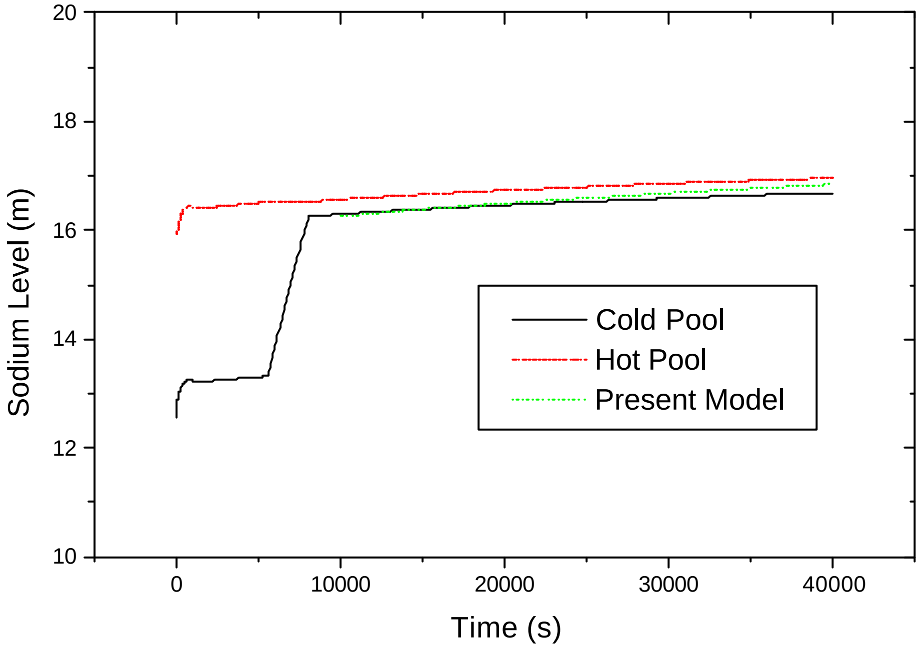

Fig. 8 Comparison of Present Model and SSC-K Calculations for Sodium Level

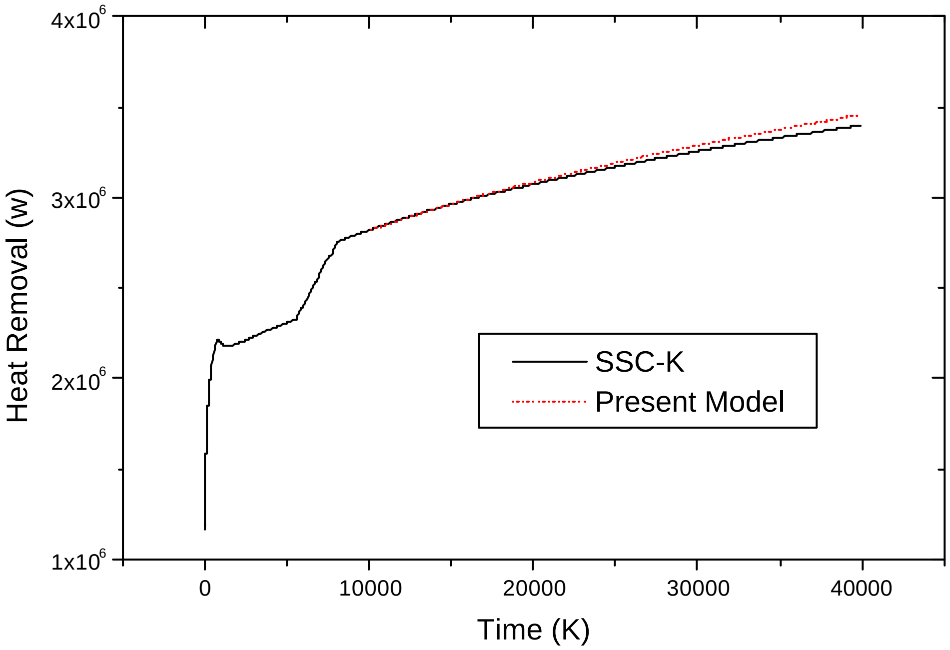

Fig. 9 Comparison of Present Model and SSC-K Calculations for PSDRS Heat Removal

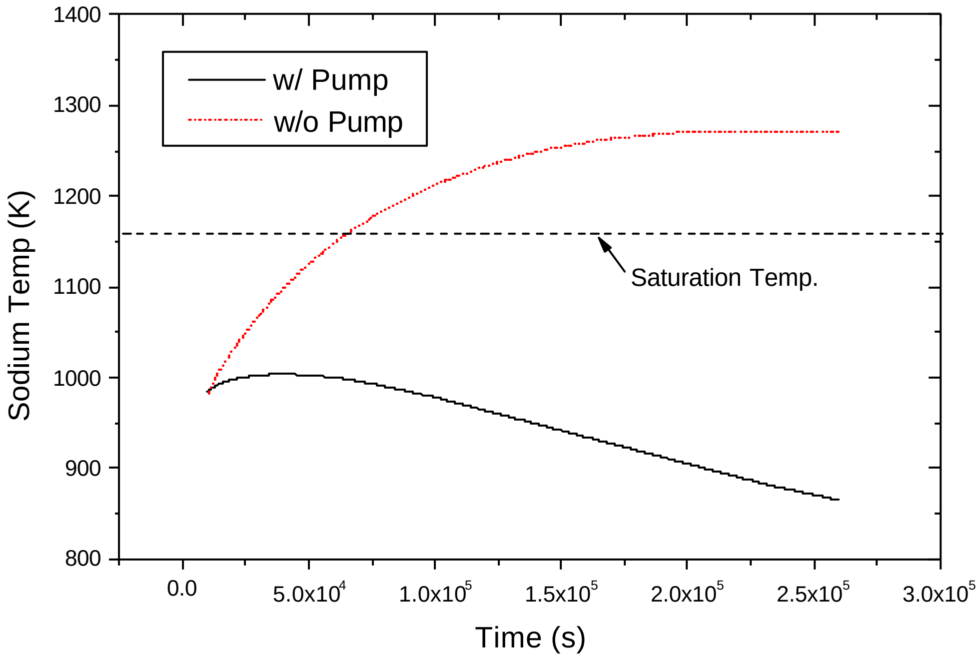

Fig. 10 Long Term Sodium Temp. Behavior with and without Pumps

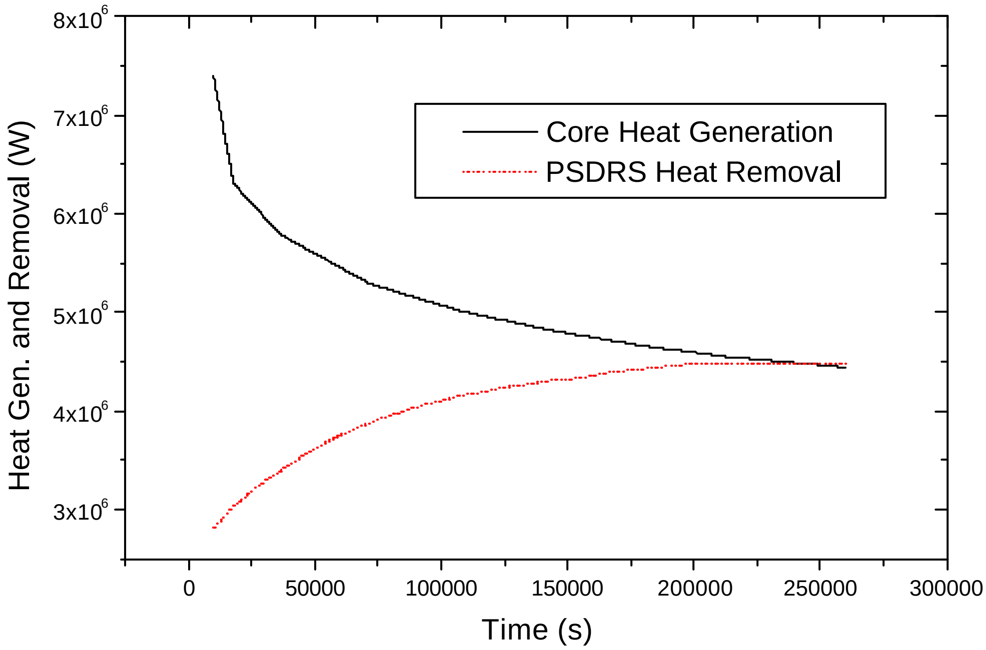

Fig. 11 Long Term Energy Balance with Pumps

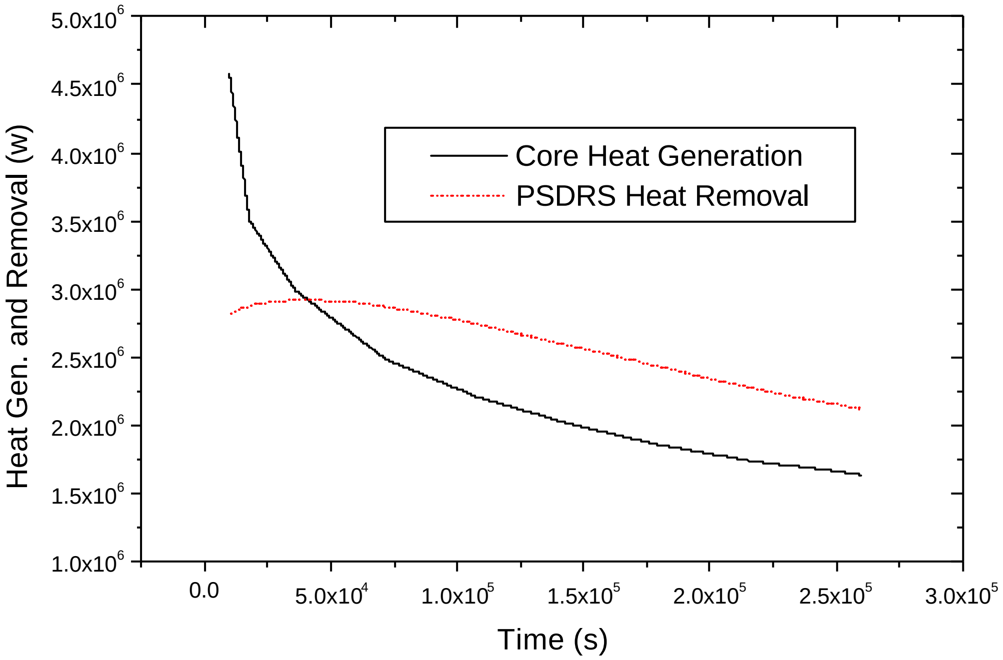

Fig. 12 Long Term Energy Balance without Pumps